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Towards sustainable agriculture: fossil-free ammonia

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Abstract

About 40% of our food would not exist without synthetic ammonia (NH_3) for fertilization. Yet, NH_3 production is energy intensive. About 2% of the world's commercial energy is consumed as fossil fuels for NH_3 synthesis based on the century-old Haber-Bosch (H.-B.) process. The state of the art and the opportunities for reducing the fossil energy footprint of industrial H.-B. NH_3 synthesis are discussed. It is shown that even a hypothetical utterly revolutionary H.-B. catalyst could not significantly reduce the energy demand of H.-B. NH_3 as this is governed by hydrogen production. Renewable energy-enabled, fossil-free NH_3 synthesis is then evaluated based on the exceptional and continuing cost decline of renewable electricity. H.-B. syngas (H_2, N_2) is assumed to be produced by electrolysis and cryogenic air separation, and then supplied to an existing H.-B. synthesis loop. Fossil-free NH_3 could be produced for energy costs of about $232 per tonne NH_3 without claiming any economic benefits for the avoidance of about 1.5 tonnes of CO_2 released per tonne NH_3 compared to the most efficient H.-B. implementations. Research into alternatives to the H.-B. process might be best targeted at emerging markets with currently little NH_3 synthesis capacity but significant future population growth such as Africa. Reduced capital intensity, good scale-down economics, tolerance for process upsets and contamination, and intermittent operability are some desirable characteristics of NH_3 synthesis in less developed markets, and for stranded resources. Processes that are fundamentally different from H.-B. may come to the fore under these specific boundary conditions.

Keywords

Ammonia; Haber-Bosch; renewable; fossil-free; fertilizer; economical

Highlights

- There is no motivation for research to improve or replace Haber-Bosch catalysts due to the overwhelming impact of hydrogen production on the economics and the energy footprint.
- The cost of electricity from renewables has sharply declined and will likely continue to do so.
- Haber-Bosch ammonia synthesis facilities can be retrofitted with existing technology for competitive wind electricity-based feedstock preparation to produce fossil-free ammonia.
- Research for alternatives to the Haber-Bosch process should be directed at emerging market and stranded resource requirements instead of attempting to replace existing Haber-Bosch facilities.

1 Introduction

The world scale and impact of ammonia synthesis

Each year, about 174 million tonnes of ammonia (NH_3) are synthesized globally (*1*), making NH_3 the second most produced man made chemical. More than 85% of NH_3 is used in fertilizers, with the remainder used mainly by other areas of the chemical- and process industries. NH_3 is produced by using a significant amount of energy to convert the hydrogen from water, and nitrogen from air to NH_3. Water is always the hydrogen source, both directly as process steam, and indirectly as the water absorbed by ancient biomass, and now used as hydrogen from methane as natural gas. The prevalent energy source is combustion of natural gas (U.S., Middle East) or coal (mainly in China) to CO_2. About 600kg of natural gas are consumed to produce 1000 kg NH_3 in the most efficient facilities.(*2*,*3*) The total fossil CO_2 emissions from NH_3 synthesis with the current basket of energy sources can be estimated at more than 670 million tonnes per year. This estimate is based on the tonnage of ammonia made using natural gas or coal, and the known estimate of CO_2 emission from using either feedstock.(*4*,*5*) This amounts to about 2.5% of all fossil fuel based CO_2 emissions world wide (*6*). NH_3 synthesis based on renewable energy and raw materials would therefore be beneficial in moving towards a sustainable future where food and fossil fuels are decoupled.

NH_3 is at the intersection of food, energy, and water, and this nexus is attracting increasing interest due to an expected increase of the world population (*7*), the impact of climate change (*8*), and an expected world-wide decrease of arable land per capita (*9*). In the United States, about 30% of commercial energy spent to produce crops is used to synthesize NH_3 (*10*). NH_3 enables 30-50% of agricultural crop output (*11*) and conserves water by increasing the crop yield per unit water used (*12*,*13*). The escape of unused agricultural fertilizers into the environment is of significant concern. Attempts are being made through precision agriculture (*14*), and modified application methods (time-release etc., (*15*)) to address this. Environmental concerns and farmer's interests are aligned since unused fertilizer is a significant financial loss to farmers.

Synthetic NH_3-based fertilizers will remain essential to the survival of a significant and increasing fraction of the world population far into the future (*16*). Obtaining nitrogeneous fertilizer from animal or human waste at an impactful scale would require collection, transport, storage (due to seasonal demand), and processing of vast amounts of manure with relatively low concentrations of bio-available N, with the concomitant energy- and economic expenditures, and environmental impact. About 5% of U.S. cropland is currently fertilized with manure. Due to the above issues and many additional barriers human and animal waste is unlikely to significantly impact the need for synthetic fertilizers (*17*). Another aspect of the global impact of the presence or absence of bioavailable nitrogen is lack of bioavailable nitrogen

hampering carbon sequestration from the atmosphere as biomass (*18*). There are considerations of adding man-made bioavailable nitrogen to natural systems for example for fertilization in the ocean to sequester fossil CO_2 (*19*).

The capacity of NH_3 to serve as a convenient hydrogen (H_2) carrier (*20*), or to be used directly as a hydrogen-rich fuel or fuel additive in internal combustion engines is an emerging aspect. Compared to H_2, NH_3 is liquefied fairly easily and liquid NH_3 exceeds the U.S. Department of Energy's (DOE) target for hydrogen storage per volume. Bulk NH_3 storage and transport by pipeline, rail, and truck, and delivery down to the retail scale is well established, as opposed to transport, storage, and distribution of H_2. This has been recognized and well described in a recent funding opportunity made available by DOE (*21*).

In summary, world production of synthetic NH_3 will have to increase significantly from now about 174 million tonnes per year during the next decades as the world population increases, specifically in Africa. Use of NH_3 as a renewable fuel and energy storage mode might further increase this demand.

Rising world-wide interest in ammonia

Significant U.S. government programs amounting to in excess of U.S. $30 million in 2016 alone towards aspects of NH_3 synthesis and applications have recently emerged and will result in an invigorated interest in NH_3 synthesis and applications in the coming years (*21*, *22*, *23*, *24*, *25*). Activities in Japan and Europe towards using NH_3 as a mode of energy storage and transport are also on the rise (*26*, *27*, *28*), often in form of public/private partnerships.

In light of the substantial decline of the cost of renewable electrical energy in the U.S., and due to the rising interest in NH_3 synthesis and applications, it seems timely to estimate if renewable electricity might be an avenue to fossil-free NH_3, and thereby substantially reduced dependency of food on fossil fuels. The state of the art process is reviewed below, followed by an assessment of renewable electricity enabled Haber-Bosch NH_3 synthesis.

Review of the state of the art Haber-Bosch process implementation

There are two major challenges to NH_3 synthesis: first, activating dinitrogen (essentially somehow breaking the exceptionally strong dinitrogen triple bond), and second, obtaining hydrogen to convert activated nitrogen to NH_3. The former allows a process to exist, but the latter governs the energy demand and economic viability (as shown below). Both tasks must be done at technologically acceptable conditions and at a cost commensurate with the value added by using ammonia in agriculture. Fritz Haber's Nobel Prize (*29*) was for fundamentally solving the nitrogen activation issue. He secured economical success by patenting recycling of valuable unreacted syngas after separating NH_3. Carl

Bosch's Nobel Prize ((*30*), with F. Bergius) relates in large part to the economical large-scale supply of hydrogen for NH_3 synthesis. Their work created the commercial fertilizer industry and averted imminent worldwide food shortages.(*31*) There were even at the time of Haber's discoveries a number of competing approaches to synthesize NH_3 at the technical scale, but none of them could match the economics of the integrated Haber-Bosch process (*31*). However, these economics are based on fossil fuels and of course do not take the impact of the release of fossil CO_2 into the atmosphere in account.

A brief review of the Haber-Bosch (H.-B.) process will show that today's challenge for large-scale NH_3 synthesis is no longer the catalytic conversion of dinitrogen and dihydrogen to NH_3. While the technology is complex, the chemistry is simple: hydrogen and nitrogen combine to produce NH_3. Figure 1 shows both the overall chemical process to produce the syngas (H_2, N_2) for the H.-B. synthesis, and the chemical reaction taking place in a H.-B. reactor.

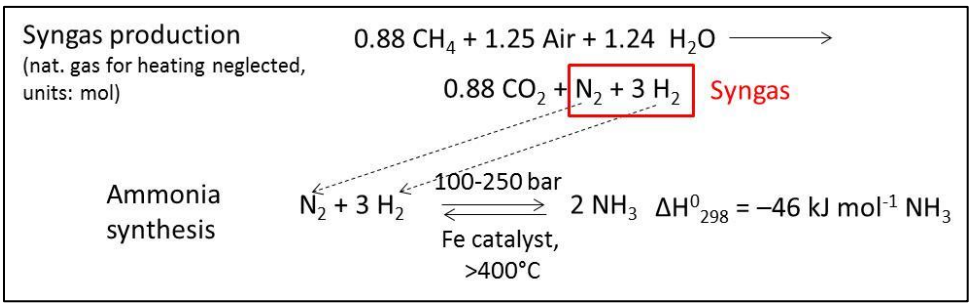

Figure 1 NH_3 synthesis, top: state of the art overall chemical reaction to produce synthesis gas (syngas) from air, water, and natural gas; bottom: the reaction in the Haber-Bosch synthesis reactor proper.

Figure 2 shows the main sections of what is generally termed the H.-B. process using the most energy efficient state of the art approach based on natural gas as both feedstock and energy source. The reader is directed to the literature for exhaustive treatment of many variations such as using coal as energy source, sophisticated changes of heat integration of the process steps, catalysts, catalyst fundamentals, and many other issues (*32*, *33*). The discussion below attempts to use the current best available technology characteristics.

The most efficient implementations of the natural gas steam reforming based H.-B. process today at industrial scale use about 600 kg of natural gas per 1000 kg anhydrous NH_3 produced (as used in Figure 2), or about 6.8 Gcal/tonne NH_3 (as natural gas lower heating value, LHV). Various plants may however use significantly more energy depending on the technology in use. If coal is used, the energy demand may approach at best 1.7 times that of an efficient natural gas based plant.

Over the last 100 years, engineering and heat integration of the overall process has led to an approach to the thermodynamic minimum energy demand that is quite impressive. The thermodynamic minimum

has been estimated at 4.98 Gcal/tonne NH_3 (as natural gas lower heating value, (*3*)). 5.10 Gcal/tonne NH_3 (product liquid ammonia) has been reported as the thermodynamic minimum elsewhere ((*34*), higher heating value, HHV). Overall, current full scale (1000 tonnes per day NH_3 and larger) energy consumption of the best technology available is therefore only about 20% above the immutable thermodynamic minimum when using the state of the art natural gas based Haber-Bosch process outlined below.

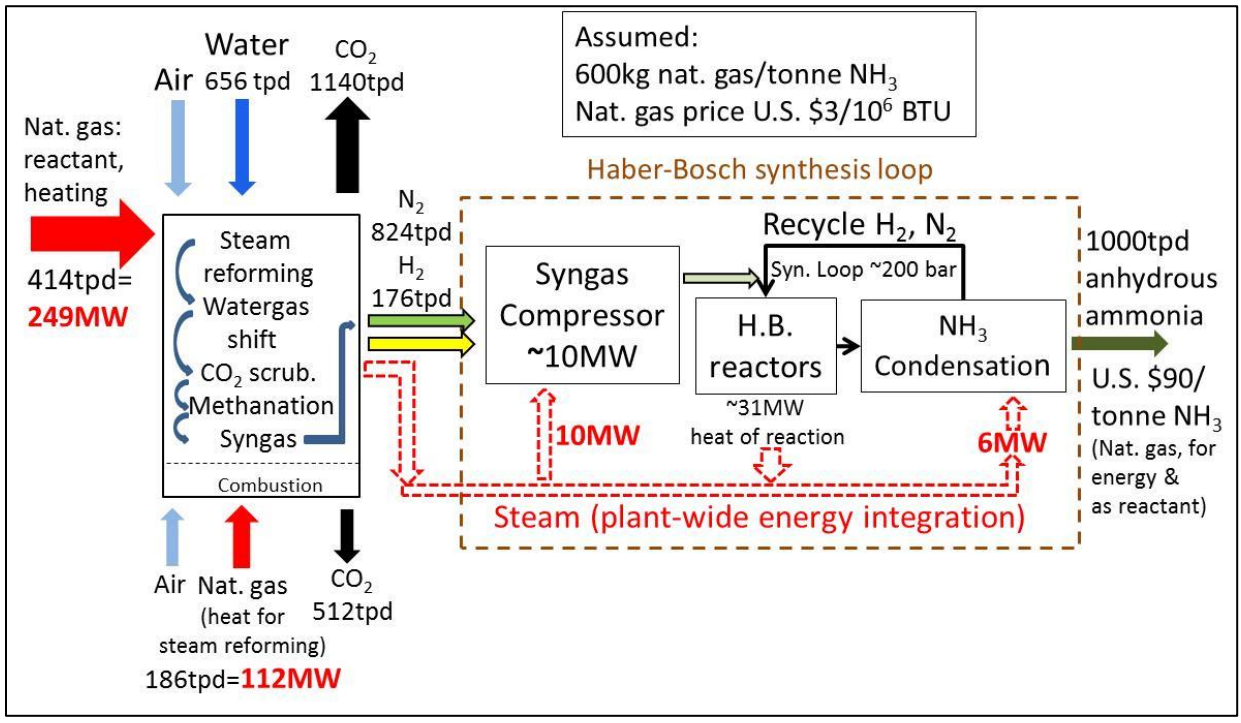

Figure 2 The state of the art Haber-Bosch process to produce NH_3 from natural gas (methane). Natural gas is used to provide energy for steam reforming using combustion, and also to provide both hydrogen and nitrogen by steam reforming and subsequent water gas shift (left). (tpd = tonne per day)

The single-pass conversion in the Haber-Bosch reactors depends on a number of operational parameters such as the level of inerts like argon. It is reported often at less than 20%, certainly no more than 30% (*4*,*35*). Unreacted hydrogen and nitrogen is always recycled (at pressure) after NH_3 is condensed and separated. The synthesis loop carries an inert load (argon from air, methane from methanation) that is controlled by purging a small stream (not shown). Oxygen or oxides must not enter the synthesis loop since this would inactivate the catalyst. Catalyst charge lifetimes are on the order of many years in industrial practice.

The steam to drive the synthesis loop compressor is generated through heat recovery from the primary reformer and cooling of the highly exothermal NH_3 synthesis reaction, with additional steam left for other purposes such as driving compression for refrigeration to condense ammonia, or for export.

The price of ammonia and energy to produce ammonia

The price of ammonia is closely related to the price of the feedstock (36, 2013 data). Labor and other (tax, insurance etc.) add perhaps 25% in the U.S. or Russia, while the high price of feedstock in Europe compared to the U.S. essentially drowns out all other costs. The historically close tracking of NH_3 price and natural gas cost has relaxed in the U.S. since 2008 due to strong demand for NH_3 and the resulting price increase. For 2016, a price of $500-600 per tonne ammonia has been reported, with a minimum of $499 per tonne since 2008 (*37*).

Above, the price for natural gas is assumed at a perhaps optimistic $3/MM BTU. Predictions of the natural gas price would be extremely speculative. Renewable electricity is assumed at $0.0235/kWh as verified by DOE, and reported to be highly likely to decrease in the future (*38*).

Further research on Haber-Bosch catalysts has essentially no impact on energy demand per tonne of ammonia

The close approach to thermodynamic limits for the full-scale existing H.-B. process imposes harsh requirements on any aspirations to improve over H.-B. as far as energy consumption per unit NH_3 produced.

If one assumes quite hypothetically operating the synthesis loop using a revolutionary catalyst at atmospheric pressure and room temperature and simultaneously improved catalyst performance, then this extremely unlikely scenario will only offer a few percent overall energy savings (see Figure 2). This further illustrates that NH_3 synthesis equals hydrogen synthesis from an economic (and thereby energy-) standpoint, as Carl Bosch pointed out. While there may exist academic or scientific reasons to further pursue, for example, improved H.-B. catalysts, there is no need or opportunity to do this for reduction of the energy consumption (*39*), or to work towards renewable NH_3. Nevertheless, NSF has called for improved catalysts for the H.-B. process to reduce the energy demand for synthetic NH_3 in two requests for proposals (*22*, *40*) although obtaining H_2 clearly consumes the vast majority of the energy for NH_3.

Research related to Haber-Bosch

A number of approaches are under investigation to replace (*41*,*42*,*43*,*44*,*45*,*46*) or improve the H.-B. process. Research on improvement has focused on new catalysts (see above) and scientific advances including a recent Nobel Prize closely related to H.-B. catalysis (*47*). Current industrial catalysts are already highly optimized and last for many years, while little further practical impact is possible due to limitations that cannot be addressed by catalysts (*39*, also discussion above). Citing Carl Bosch, in 1932, on the importance of further improvements to the catalytic H.-B. loop compared to the cost of obtaining hydrogen feedstock, "… the conversion of the ready-made gas mixture into ammonia is only a minor cost factor"(*30*). More than 80 years later, this still holds true.

As an example of proposed alternative processes to replace H.-B., one recent approach is the use of a "cold" plasma to produce ammonia from hydrogen and nitrogen (*48*). The "hot" plasma approach using an electrical discharge has been implemented at full scale early in the 20th century and was quickly discarded due to the exceptionally high energy demand compared to H.-B. (*49*). Using the data from the above reference, cold plasma would require about 40,000 MW for a 1000 tonne NH_3 per day production level, while industrial-scale state of the art H.-B. requires about 360 MW. The energy demand of cold plasma for ammonia synthesis appears clearly prohibitive.

Electrochemical approaches to replace H.-B. are also being proposed and explored at the laboratory level. Using published data as an example (*41*) the electrochemical approach would require more than twice the energy per tonne of NH_3 produced compared to H.-B., assuming no loss of energy efficiency from extremely well controlled laboratory conditions to full industrial scale with realistic feedstock and chemicals.

Ammonia synthesis based on nitrides and solar energy has been estimated to be competitive to existing state of the art H.-B. facilities (*50*). The advantages of the process, however, relate more to operation near ambient pressure vs. several hundred atmospheres for H.-B., and the use of rugged bulk chemical conversions instead of the sensitive H.-B. heterogeneous catalysts.

Below it is shown that renewable H.-B. NH_3, based on available full-scale electrolysis technology to produce hydrogen and cryogenic air separation to produce nitrogen, is now becoming economically attractive due to the exceptional decrease in the cost of renewable electricity (*38*). The basic approach is to take full advantage of the highly optimized H.-B. process and existing installed capital, with a bolt-on solution to provide syngas.

Realistic opportunities for Haber-Bosch alternatives

A need for new simple, rugged, and down-scaleable processes exists where H.-B. is not economical or practical: small scale, with operation on intermittent renewable electricity, in less developed countries without an existing NH_3 industry or reliable infrastructure, and where upsets may be more frequent.

From an economical perspective, commodities such as NH_3 produced in capital-intensive facilities at large volumes with modest profit per unit, suffer from significant barriers to entry for proposed novel greenfield processes. This is especially true in markets such as the U.S., Europe, China, or the Middle East where a large base of installed, conventional H.-B. capital is present and growing, and will operate for decades to come absent regulatory intervention. Taking advantage of the installed capital base of H.-B. ammonia facilities, with about 29 facilities in the U.S. alone (*1*), retrofitting would lower the barriers for renewable ammonia to enter the market. This approach is taken below.

2 Results and Discussion

The basis for the proposed renewable ammonia process evaluated herein is 1000 tonnes of anhydrous ammonia produced per day (1000 tpd), a representative size of a commercial unit (Figure 2). Renewable hydrogen can be derived from water by solar thermal processes (*51*). However, electrolysis of water for hydrogen production is commercially available at scale and is therefore assumed here as the hydrogen source for ammonia synthesis from renewable electricity.

The overall premise is to retain the existing H.-B. synthesis loop to make use of installed capital investments. The hydrogen and nitrogen generation from natural gas (steam reforming/watergas shift, state of the art Haber-Bosch plants) is replaced with electrolytic hydrogen, and cryogenic nitrogen is made using renewable electricity. This replacement could also be done step-wise in form of incremental capacity, or debottlenecking if steam reforming of natural gas limits capacity.

The methodology applied here concentrates on the energy input to produce a unit of anhydrous ammonia. This is quite simple when electrical energy is used to produce syngas by electrolysis of water, and cryogenic air separation, respectively, especially since energy for the H.-B. synthesis loop is essentially negligible. The feedstock is either available at no cost (air), or at marginal energy input (water purification, see below). The reference case for natural gas-based state of the art NH_3 production intertwines energy and chemical feedstock somewhat since some hydrogen is derived from water (steam), and some from natural gas that also supplies energy. The operating cost, however, can be compared through the price per unit of energy, either as natural gas or as electricity. This is done below.

Hydrogen and nitrogen production

In the proposed system, renewable NH_3 is produced by electrolyzing water to obtain highly pure hydrogen (alkaline electrolysis or proton-exchange membrane electrolysis, assumed at 54 kWh per kg H_2 delivered at 30 bar (*52*,*53*)). Electrolytic hydrogen has the added advantage of not containing catalyst poisons (especially sulfurous compounds), compared to using natural gas. Purified nitrogen is produced by a cryogenic air separation unit (243 kWh per tonne N_2 delivered at 285K, 40 bar (*54*)). A conventional oxygen-removal step (not shown) to purify the cryogenic nitrogen is needed due to the great oxygen sensitivity of H.-B. catalysts.

Synthesis loop compressor

A single multi-stage centrifugal syngas compressor used in state of the art existing H.-B. synthesis loops is typically driven by a steam turbine and requires about 10 MW to compress the synthesis gas for the assumed 1000 tpd NH_3 production (*55*). Steam is conventionally derived from the natural gas steam reforming process, and from cooling the H.-B. reactors. The conceptual cryogenic air separation and

electrolysis assumed here do not produce significant amounts of steam to drive the compressor. However, up to 31 MW of heat of reaction is still available as high-pressure steam from required cooling of the Haber-Bosch synthesis reactors (*3*, *56*). Estimating 30% efficiency for the use of the high-pressure steam in the syngas compressor, the available steam would nominally suffice to drive the syngas compressor. An amount of renewable energy may be needed to raise additional steam for the compressor, but even an electrical drive would have marginal impact compared to the energy for H_2 generation.

As their relative contributions are small, energy for the following is neglected: gas recycling inside of the Haber-Bosch synthesis loop, and motive force to transport various gases and liquids.

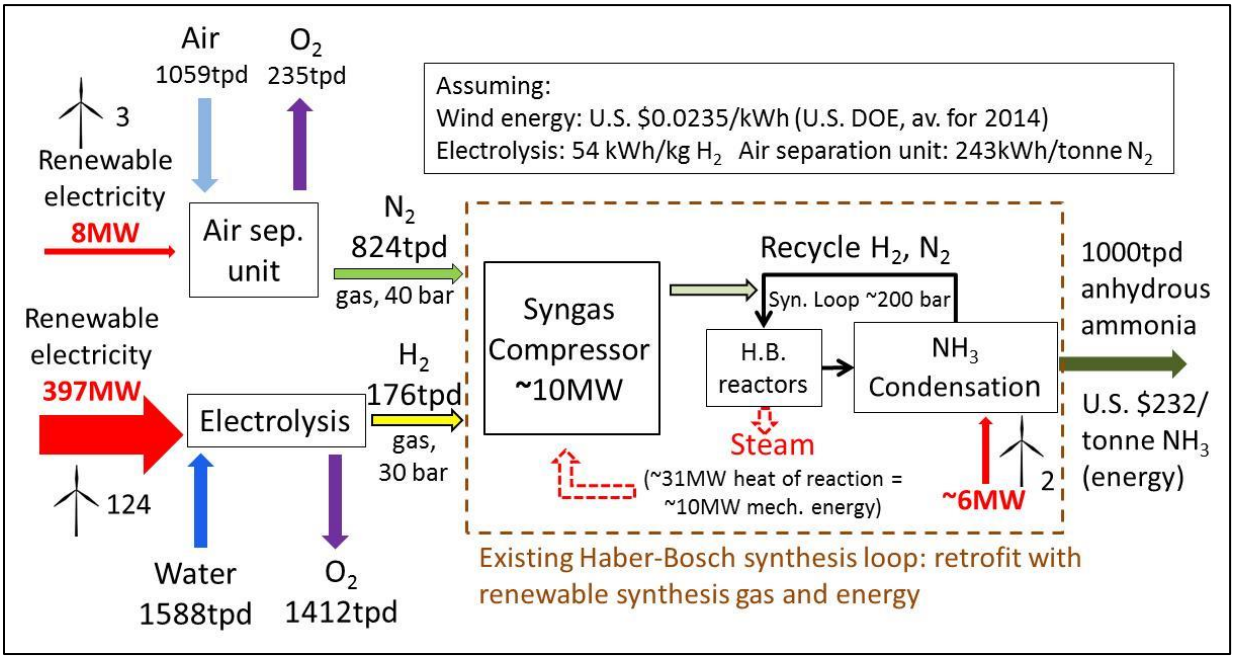

Figure 3 Hydrogen generation governs the energy demand for the synthesis of 1000 tonnes per day (tpd) of renewable ammonia in a "bolt-on" concept. Renewable cryogenic N_2 and renewable H_2 from water electrolysis are fed to an existing Haber-Bosch synthesis loop. Electrolysis is assumed at 54 kWh/kg H_2. Cryogenic N_2 is assumed at 243 kWh per tonne N_2. Wind turbines are assumed operating at 3 MW each for a simple illustration, disregarding the capacity factor.

Detailed discussion of costs

Hydrogen production by electrolysis consumes 94% of the renewable electricity required according to Figure 3. The U.S. nationwide average electricity price to industrial customers in 2014 was $0.071 per kWh (*57*). Renewable energy prices have declined precipitously, with an average of $0.0235 per kWh for power-purchase agreements from wind energy reported for 2014 in the U.S.(*58*) If a total of 411 MW is required (Figure 3) for the benchmark 1000 tpd ammonia production, then the energy cost for renewable electricity would be $232 per tonne of ammonia produced. No significant amount of fossil fuel would be needed.

Transportation costs in the U.S. are negligible compared to the cost of producing NH_3 (*59*,*60*). Feed water for the electrolysis can be produced from seawater (worst-case / highest-cost scenario) by reverse osmosis for $1.20 per tonne of ammonia including maintenance and capital expense charges (*61*), at about 3 kWh per cubic meter of water produced, resulting in a total cost of $233 per tonne of anhydrous renewable NH_3. Seventy to eighty-five percent of ammonia production cash cost resides in the cost of energy (*62*), with the U.S. at the top of this range (energy as natural gas, for the state-of-the-art H.-B. process). Taking this in account, it can be estimated that cash costs would be $251 per tonne of anhydrous renewable ammonia based on electricity from wind. The market price of ammonia is quite variable but for comparison, the minimum price of ammonia was reported at $499/tonne for the time period of 2008-2016 (*37*).

Any credit for eliminating the current minimum of about 1.5 tonnes of CO_2 emissions per tonne of ammonia produced would improve fossil-free ammonia economics. Further improvement would result if the high-purity oxygen by-product could be used, perhaps for oxygen-blown fossil fuel combustion to enable carbon capture/sequestration, or for other purposes such as steel making or bleaching for the pulp and paper industries.

Comparison to previous work on electrolysis based ammonia

The calculations above are verified against earlier work by Grundt et al. at Norsk Hydro a. s. (*63*). Grundt et al. reported an overall energy demand of 416MW for 1000 tpd for a Haber-Bosch ammonia plant design using water electrolysis and air separation. This resulted in energy costs of U.S. $217 per tonne of ammonia produced, using today's $0.0235 per kWh, nearly identical to the result above. Elsewhere (*64*), Dubey evaluated a technically similar but energy-island-based scenario for small-scale, wind- and electrolysis based H.-B. NH_3 (77 tonnes per day or less). This included hydrogen storage to continuously generate electricity using generators (for air separation etc.), and NH_3 when wind would be not available. Simply extrapolating Dubey's small-scale data to the benchmark 1000tpd results in about twice the electrical energy demand compared to Grundt et al. and the calculations above. This difference is mainly due to the added H_2 storage/usage, and the less efficient small-scale cryogenic nitrogen-generation system.

Grundt et al. estimated capital expenses of U.S. $200 million (corrected to 2016 dollars) for a 1000-tpd ammonia facility (H.-B. synthesis loop, water electrolysis, and cryogenic air separation). Applying the six-tenths rule of plant design, a 2000tpd facility would have estimated capital costs of $329 million. Capital investment for conventional H.-B. facilities are essentially equivalent at U.S. $312 million for 2000-tpd capacity (natural gas-based, state-of-the-art, greenfield H.-B. facility (*65*)). Thus, even for a greenfield facility, renewable ammonia capital costs are competitive with natural gas-based ammonia.

Grundt et al.'s capital investment figure will obviously be significantly reduced if an existing Haber-Bosch synthesis loop is retrofitted with renewable syngas production.

Avenues to renewable ammonia:

The very significant existing capital investments in natural gas- or coal-based ammonia synthesis via H.-B. in countries such as China and the U.S. causes an amount of inertia to technological change that is hard to overcome. The "bolt-on" conversion or partial conversion to hydrogen and nitrogen from water and air based on renewable electricity, however, can perhaps overcome this inertia through strong payback as demonstrated here, or perhaps by marketing renewable fertilizer or NH_3 that may be attractive even at a premium for organic food production or energy storage/transportation (*26*).

The capital investment inertia in Africa is much lower since little ammonia is used or synthesized on the continent, relative to the current and future population. However, the technical complexity, economic barriers to down-scaling, and capital intensity of state-of-the-art H.-B. facilities makes the process less compatible with the economic, technological, and infrastructure realities in Africa. Research for NH_3 synthesis completely different from H.-B. should address enabling factors of future markets like Africa: economical down-scaling to regional or local scale to avoid the need for transport networks, robustness and resilience to upsets or utility interruptions, intermittent operability from intermittent renewable resources, and technological simplicity.

3 Conclusions

The precipitous decline in the cost of renewable electricity renders electrolysis of water and cryogenic nitrogen from air a feedstock supply route for Haber-Bosch ammonia synthesis gas that is increasingly competitive with natural gas-based Haber-Bosch ammonia. Using available industrial-scale technology, the energy demand for a process based on electrical energy to provide hydrogen and nitrogen is about 14% higher than for the conventional natural gas based process. Existing Haber-Bosch synthesis loops in ammonia synthesis facilities in the U.S. and worldwide could be incrementally or completely retrofitted. Developing retrofit technology would perhaps also be useful for the Chinese market for the future (*66*). There is now a clear, economically attractive and relatively rapid path to decouple ammonia synthesis as a major energy component of food production from fossil fuel, especially where renewable electricity already is increasingly inexpensive, such as in the U.S. and Europe.

Research into Haber-Bosch catalysts or replacements for those catalysts will have little to no impact on the energy demand or fossil fuel footprint of ammonia synthesis since hydrogen production consumes the Lyon's share of energy. Even a hypothetical catalyst allowing room temperature operation at

atmospheric pressure with superior performance compared to existing Haber-Bosch catalysts will have essentially no impact on the energy footprint.

Research into fundamental alternatives to the Haber-Bosch process should therefore concentrate on conditions in future markets such as Africa where farmers use little fertilizer, ammonia production is at a low level, and future population growth and increase in food demand is expected to be the most significant. Issues such as economical down-scaling, reduced complexity by atmospheric pressure operation, lower capital expense, tolerance to upsets, and ease of intermittent operability would enable future greenfield ammonia production in Africa.

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